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## The first stages of the evolution of Globular Clusters

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**Abstract.** The majority of the inhomogeneities in the chemical composition of Globular Cluster (GC) stars appear due to primordial enrichment. The most studied model today claims that the ejecta of Asymptotic Giant Branch (AGB) stars of high mass —those evolving during the first  $\simeq 100$  Myr of the Clusters life— directly form a second generation of stars with abundance anomalies. In this talk, we review the status of the art with regard to this model, whose major problems are *i*: the modelling of the chemical anomalies is still not fully complete, and *ii*: it requires an IMF peculiarly enhanced in the intermediate mass stars. The model predicts enhanced helium abundance in the stars showing chemical anomalies, and the helium abundance distribution can be roughly derived from the morphology of the horizontal branch. Such distribution may possibly help to falsify the model for the first phases of evolution of GCs. As an illustration, we compare the results of the analysis of the HB morphology of some clusters.

### 1. Introduction

The observations of GC stars are still to be fully interpreted in a consistent frame. Nevertheless, there are a few solid statements which can be put together starting from observations. In the following we will examine the paradigm of self-enrichment and point out clearly what is a “must” and what is only a suggestion.

As Raffaele Gratton pointed out in his talk, the latest years have seen a plethora of beautiful observations of abundances in Globular Cluster stars. These help to clarify the issue of “chemical anomalies” that dates back to the seventies. The anomalies are now observed also at the turnoff (TO) and among the subgiants (e.g., Gratton et al. 2001; Briley et al. 2004), so they must be attributed to some process of “self-enrichment” occurring at the first stages of the cluster life. Therefore, there has been a first epoch of star formation which gives origin to the “normal” (first generation) stars, that have CNO and other abundances similar to the population II field stars of the same metallicity. Afterwards, there must have been some other epoch of star formation, including material heavily processed through the CNO cycle. This material either was entirely ejected by stars belonging to the first stellar generation, or it is a mixture of ejected and pristine matter of the initial star forming cloud. We can derive this statement as a consequence of the fact that there is no appreciable difference

in the metallicity of the “normal” and chemically anomalous stars belonging to the same GC<sup>1</sup>. This is an important fact that tells us, e.g., that it is highly improbable that the chemical anomalies are due to mixing of stars born in two different clouds, as there is no reason why the two clouds should have a unique metallicity. In addition, the clusters showing chemical anomalies have a huge variety of metallicities, making the suggestion of mixing of two different clouds even more improbable. Therefore, the **first statement** we can make is: *the chemically anomalous matter which we see in the atmospheres of the chemically anomalous GC stars, has been processed by stars belonging to the first stellar generation*. This statement does not preclude that the “first generation” stars, which we see today, and the progenitors of the CNO processed matter, could have been, initially, part of a population much larger than today’s GC. This, in fact, may be necessary to understand the present number ratios of stars belonging to the first and second generation in different GCs.

Presently, there have been interesting attempts to attribute the chemical spreads to star formation in the initial proto-GC cloud matter heavily contaminated by the ejecta of massive stars fastly rotating at velocities close to break up (Decressin et al. 2006), a view which is presented here by Corinne Charbonnel. In this talk we review the status of the art of the “classic model”, which attributes self-enrichment to a second star formation phase occurring after the last Supernovae type II exploded in GCs (the ejecta of SNaE are carried easily away from the clusters due to their high velocity), when the massive Asymptotic Giant Branch (AGB) stars were evolving. Starting some  $\sim 5 \times 10^7$ yr from the birth of the first stellar generation, the massive AGBs cycle their envelope material through hot CNO-cycle at the bottom of their convective envelopes (Hot Bottom Burning –HBB) and lose them in low velocity winds, which may remain inside the cluster and begin a second star formation epoch.

## 2. Is the chemistry of massive AGB envelopes resembling the anomalous chemistry in GCs?

The HBB that occurs at the bottom of the convective envelopes in luminous AGB stars is very efficient in a low metallicity environment such as the one in GCs. While in Population I the main result of HBB is Lithium production and CN cycling —so that luminous AGBs lose their Carbon star status—, at low metallicity also the ON cycle is efficient, and Oxygen is destroyed (Ventura et al. 2001). The composition in these envelopes then depends on the one side on the efficiency of HBB, and on the other side on the occurrence of the third dredge up, which brings into the envelope the products of nuclear reactions occurring in the helium shell during the thermal pulses. The chemistry of anomalous stars in GCs however does not show any sign of processing in helium burning regions: no indication of s-process enhancement, nor of increased abundances in the sum of CNO elements (Ivans et al. 1999; Briley et al. 2002; Cohen & Meléndez 2005; Cohen et al. 2005). Consequently, either the AGB stars are not the site of nucleosynthesis of the matter constituting the chemically anomalous stars, or, we have

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<sup>1</sup>Needless to say, this statement *does not* hold for  $\omega$  Cen, which must indeed be considered a small galaxy and not a typical GC.

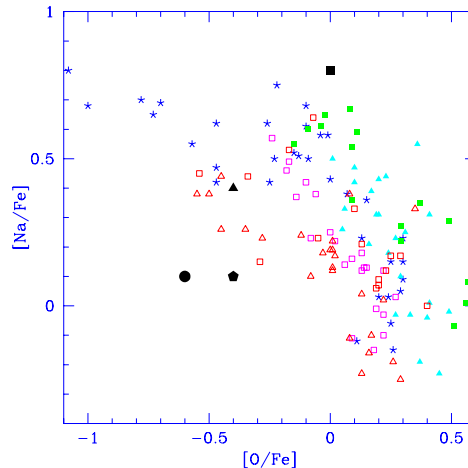


Figure 1. : O-Na anti-correlation for stars in several globular clusters. Small symbols indicate stellar abundances (see Ventura & D’Antona (2005b) for details).  $[O/Fe]$  abundances below  $\sim -0.5$  can not be explained by self-enrichment by AGB. The big full (black) symbols represent models for  $5M_{\odot}$  published in Ventura & D’Antona (2006). The square is the MLT model, the pentagon and the circle are the standard FST model and the model in which the mass loss rate is reduced by a factor two, respectively. The triangle is the model in which the lower limit of the cross section of the reaction  $^{23}\text{Na}(p,\alpha)^{20}\text{Ne}$  is assumed.

the **second statement**: *if the AGBs are the source of the chemical anomalies, only the most massive intermediate mass stars are involved*, those which process Oxygen to Nitrogen at the bottom of the convective envelope, but have mass loss rates so high that they pass through few thermal pulses and have only few episodes of the third dredge up. Ventura & D’Antona (2005a) have shown that Oxygen burning is possible in models that employ a very efficient convection. In turn, the efficient convection makes the models more luminous and they lose matter and end their evolution in a shorter timescale. This explains the dramatic differences found among the results of different researchers, e.g. see the comparison between the models in Fenner et al. (2004), that employ low efficiency MLT convection, vs. the models by Ventura, D’Antona, & Mazzitelli (2002), that employ the more efficient convection model by Canuto, Goldman, & Mazzitelli (1996), as shown in in Figure 7 of Ventura & D’Antona (2005b). Based on the results from models with low convection efficiency, several researchers have in fact cast severe doubts on the reliability of the AGB self-enrichment model. The agreement between the AGB nucleosynthesis and the observations is still far from perfect. The main problem (Denissenkov & Weiss 2001) is to reproduce the O–Na anticorrelation, but this can be achieved if the cross section  $^{23}\text{Na}(p,\alpha)^{20}\text{Ne}$  is taken at the lower limit of the rate by Hale et al. (2004) (Ventura & D’Antona 2006). Figure 1 shows the observational data for the anticorrelation and the resulting abundances in the ejecta of a  $5M_{\odot}$  computed with different assumptions on the mass loss rate and on the cross sections. Notice that, in any case, the most extreme Oxygen abundances which are found in M13 (Snedden et al.

2004) reaching  $[\text{O}/\text{Fe}] \simeq -1$ , can not be obtained in HBB models: these abundances require some additional mechanism for Oxygen depletion, for example deep extra-mixing in giants (Denissenkov et al. 2006).

One of the reasons to prefer AGBs as the source of the second generation stars in GCs is the following. The (scarce) observations of Lithium in the turnoff stars in NGC 6397 (Bonifacio et al. 2002) and NGC 6752 (Pasquini 2005) indicate abundances  $\log N(\text{Li}) \sim 1.9 - 2.3$ , certainly not corresponding to abundances in a CNO heavily processed environment, *unless* this environment is the HBB AGBs, which indeed may provide such range of abundances, through the operation of the berillium transport mechanism (Cameron & Fowler 1971), as shown by Ventura et al. (2001).

### 3. The helium content of the chemically anomalous stars

A qualitative progress in the understanding of the problem was made when it was shown that an empiric characteristic of GCs already noticed in the literature (Catelan et al. 1998), namely the presence of abundance anomalies together with peculiar horizontal branch morphologies, could be due to a concomitant helium anomaly in the chemistry. D’Antona et al. (2002) remarked a possible interpretation of the morphology of some HBs, very extended in  $T_{\text{eff}}$ , in terms of an increase in the initial helium content of the cluster stars which populate the bluer parts of the HB. There is now a clear correspondence between the chemical peculiarities (in particular the O–Na anticorrelation) and the morphology of the horizontal branch (see Gratton’s talk). Interpreting this latter as an indication that the helium content of the second generation stars is larger than in the first generation, this gives a further element in favour of the AGB self-enrichment scenario (D’Antona et al. 2002; D’Antona & Caloi 2004; Carretta 2006). The proposed model requires that the helium enhancement is present in the whole body of the stars showing chemical anomalies: consequently, a model in which the chemical anomalies are due to accretion on already formed stars (D’Antona, Gratton, & Chieffi 1983; Tsujimoto et al. 2006) must be rejected. The helium yields from the massive AGB ejecta can reach  $Y \sim 0.35$ , starting from a mere  $Y = 0.24$  (the Big Bang abundance). This result is particularly robust, as it is due primarily to the so called ‘second dredge up’ phase, which is much less model dependent than the third dredge up associated with the thermal pulses. The interpretation for the HB morphology in terms of helium spread received support from the discovery that the main sequence of NGC 2808 presents an asymmetric color distribution which can best be explained by adding to the normal stars a population of 15–20% of stars with very high helium abundance ( $Y \sim 40\%$ ). For the helium distribution in the stars of NGC 2808, see the extensive discussion in D’Antona et al. (2005). The existence of peculiarly blue MSs was also found in  $\omega\text{Cen}$  (Bedin et al. 2004; Norris 2004; Piotto et al. 2005), and for further evidence see Piotto’s talk.

If we accept the AGBs as source of the hot–CNO processed material, the helium yields expected from these stars (Ventura, D’Antona, & Mazzitelli 2002) suggest the **third statement**: *the spreads in chemical abundances are actually due to the birth of successive generation of stars directly from the ejecta of the massive AGBs of the first generation*. Statements two and three suggest another

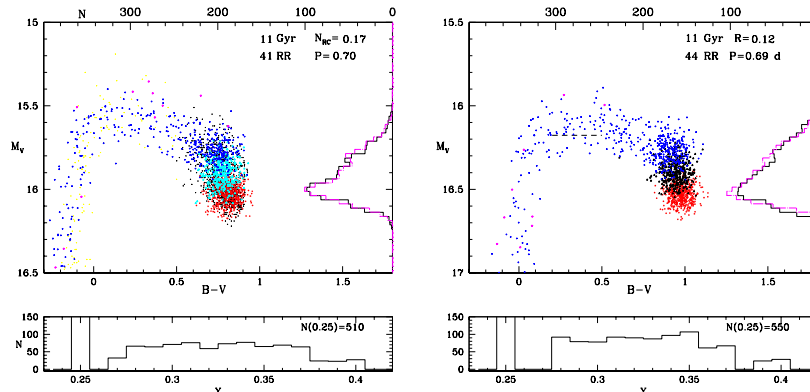


Figure 2. The fact that the stars in the metal rich clusters NGC 6441 and NGC 6388 have large variations in the helium content is not only testified by the presence of luminous RR Lyr and of an extended blue HB, but also by the luminosity distribution in the red clump. This is shown in two synthetic HB simulations for NGC 6441 (Caloi & D’Antona 2006, right panel) and for NGC 6388 (left panel, from Caloi & D’Antona, in preparation). The different colors refer to stars in different ranges of helium content. The observed clump distributions are shown on the right of each figure, superimposed to the theoretical distribution. The bottom panels show the number vs. helium distributions assumed for the simulations. The number of stars with primordial helium  $Y=0.25$ ,  $N(0.25)$ , is indicated in the labels.

important hint. There must be a somewhat constrained time for the end of the second phase of star formation: it is clear enough that the second star formation stage must stop abruptly at some epoch. In particular, the absence of s-process and CNO enhancements in the second generation stars, and the limitation in Na enhancement point towards a stop in star formation at the epoch of the evolution of stars having  $M < 3.5 - 4M_{\odot}$ . There can be several reasons for this stop, which should be modelled. For example, the additional energy input by strong UV sources such as the planetary nebulae from relatively lower mass progenitors, or by the onset of a significant SNIa contribution. In any case, stopping early enough the second stage of star formation contributes to leave a *discontinuity* between the helium content of the first generation (probably the Big Bang abundance) and the *lowest* helium content of the second generation. This produces a discontinuity in mass along the red giant branch, which reflects in a discontinuity in mass along the HB. Our **fourth statement** is: *if AGBs are the source of the hot-CNO processed material, the clusters with chemical anomalies MUST preserve a helium discontinuity between the stars of the first and second generation.* This is a constraint which is valid until we can attribute a cosmological helium content ( $Y \sim 0.25$ ) to the first generation stars. An exception in this respect may be 47 Tuc (Salaris & Weiss 1998). The presence of a helium discontinuity could falsify the self-enrichment models: if the anomalies are due to mixing of primordial gas with the gas ejected by massive stars (Decressin et al. 2006), in fact, there is no reason why a helium discontinuity should be preserved.

The lack of stars in the RR Lyr region in the cluster NGC 2808 can be considered as an indication in favour of the fourth statement. In fact this feature suggested us to use the HB “amplification” to derive information on the probable helium abundances distribution of the cluster stars (D’Antona & Caloi 2004). We can easily convince ourselves that there are many clusters which also have a gap in helium content between the two generations, but it is not so evident as in NGC 2808 because the different metallicity, mass loss (and possibly also the age) of the cluster provide HB masses which cluster either to the blue side of the HB, or into the red clump, as we will see in the following.

#### 4. The helium distribution in metal rich GCs

The helium spread, although not altering in a significant way the absolute luminosity of the RR Lyrae in clusters in which there is a consistent “first generation” population (D’Antona et al. 2002) produces, in the particular case of NGC 2808, the small but noticeable difference in luminosity between the cool side of the blue HB and the hot side of the red HB (Bedin et al. 2000), which, so far, had not been consistently explained. Caloi & D’Antona (2006) recently examined the marked bimodality of very peculiar GCs NGC 6388 and NGC 6441 (Rich et al. 1997). The metallicity of NGC 6441 has been recently confirmed to be high (Clementini et al. 2005) and is not consistent with the very long periods of the RRab variables (Pritzl et al. 2000) in these two clusters. Analysing the HB morphology of NGC 6441 in terms of a helium-rich population has provided a coherent interpretation of the three main features of the anomalous HB of this cluster: *i*: the long extension in luminosity of the red clump; *ii*: the fact that RR Lyrs have a very long average period, which is unusual for a cluster of high metallicity; *iii*: the extension into the blue of the HB.

The synthetic models for the HB of NGC 6441 showed that a helium discontinuity *must* be present (from  $Y=0.25$  to a minimum value of  $Y \simeq 0.27$ , as in the cluster NGC 2808). Is this a further confirmation of the AGB self-enrichment model? More precise photometry of the HB would possibly prove a double peak in the luminosity distribution of the red clump stars. Another interesting result of this analysis is the following: the fraction of helium rich stars, is much larger than the fraction of RR Lyr and blue stars (10 – 12%). In NGC 6441, 29% have  $Y > 0.33$  and  $\sim 14\%$  have  $Y > 0.35$ <sup>2</sup>. A large fraction of the helium rich stars is contained into the red clump, as we show in the simulations for NGC 6441 and NGC 6388 in Figure 2. In fact, the HB lifetime of metal rich, high helium stars, is spent uniformly in the red and blue parts of tracks very extended in colours (Sweigart & Gross 1976). Therefore, if there are very luminous, helium rich, RR Lyr, there must also be very luminous, helium rich, red clump stars, as we see from Figure 3, where we compare the simulated versus observed histogram of the number of stars in the red clump vs. the visual magnitude.

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<sup>2</sup>This latter figure is similar to the percentage of stars with  $Y \sim 0.4$  found from analysing the MS in NGC 2808 (D’Antona et al. 2005). Thus the origin of this tail of very high helium stars, which are not predicted from AGB model computations, may be similar in these very different GCs. But these stars represent only the *tip of the iceberg* of the self-enrichment problem

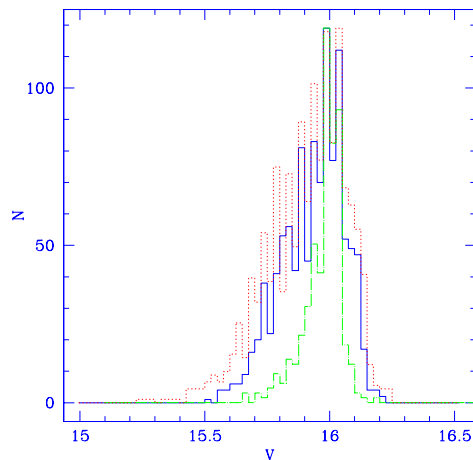


Figure 3. Plot of the observed number of stars versus magnitude for the red horizontal branch of three metal rich clusters: NGC 6441 (dots), NGC 6388 (full line), and 47 Tuc (dashed line). The magnitudes have been normalized so that the peak in the distribution coincides for all the clusters. The “thickness” in magnitude of NGC 6388 and NGC 6441 is much larger than in 47 Tuc. The excess of stars at smaller luminosities below the maximum is probably due to the larger observational errors, but the (asymmetric) excess at higher luminosities is most easily interpreted as due to stars with helium much higher than normal.

Table 1. Helium history of 4 clusters

NGC 2808		NGC 6441		NGC 6388		47 Tuc	
Y	%	Y	%	Y	%	Y	%
0.24	50	0.25	38	.25	39	.25	75
0.26-0.29	35	0.27-0.35	48	0.27-0.35	41	0.27-.32	25
~0.4	15	>0.35	14	>0.35	20		

Table 1 shows the preliminary “helium histories” of four clusters, based on synthetic models of their HBs. The analysis has been done also for 47 Tuc. The different thickness in luminosity of the red clump is the main reference for the analysis of the three metal rich clusters, while the results for NGC 2808 come from D’Antona et al. (2005). Notice that the small percentage (25%) of stars with high helium in 47 Tuc is in contradiction with the observation that CN strong and CN weak stars in the cluster are about in similar percentages (Briley et al. 2004). If *no helium gap is present*, the percentage can reach  $\sim 40\%$ . An escape from this problem can be found if the first stellar generation in 47 Tuc has a larger initial helium content (Salaris & Weiss 1998).

We have to mention also the possibility that some clusters have today only members with helium content of larger than the primordial value. This is possibly the situation in M13, one of the classic “second parameter” pair M3 and M13, according to Caloi & D’Antona (2005) suggestion. If we take this sug-

gestion seriously, the **fifth statement** is: *the fraction of 1st stellar generation (no chemical anomalies, normal Y) which is today present in the cluster can vary among clusters. The clusters with predominantly blue HB might have lost almost all the 1st generation.* Although very difficult to be accepted, this statement puts the accent on the fact that the primordial GCs might have been much more massive than today's. In this respect, the problem of the initial mass function might find a solution, if a large fraction of the first stellar generation has been lost.

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